Measurements of the Bulk Viscosity of Xenon (BVX)

The bulk viscosity ζ (or the "second viscosity") is the transport coefficient that dampens the compressional motion of a fluid, beyond the damping caused by the shear viscosity. The damping is the result of energy exchange between the fluid's translational degrees of freedom (acoustic waves or shock waves) and its internal degrees of freedom (molecular rotations, vibrations, metastable intermolecular bonds, and critical fluctuations). As the critical point is approached, the critical fluctuations grow in size and duration causing the bulk viscosity to increase. This phenomenon is universal; therefore, the knowledge gained from measuring the bulk viscosity of xenon will contribute to fundamental physics and to understanding the attenuation of shock waves in turbines driven by any supercritical fluid.

K.A. Gillis, I.I. Shinder, and M.R. Moldover (Div. 836)

The bulk viscosity ζ is the transport coefficient that dampens the compressional motion of a fluid. When a fluid is disturbed by a wave of frequency ω, the critical fluctuations relax towards equilibrium with a characteristic time ζ that diverges as $t^{-1.9}$ as the critical temperature T_c is approached. (Here, $t \equiv (T-T_c)/T_c$ is the reduced temperature.) As T_c is approached, the bulk viscosity increases with τ until the product $\omega\tau = 1$; then it levels off. Previous measurements of the bulk viscosity had two limitations. First, they were conducted at high (megahertz) frequencies so that the product ωτ reached 1 before the fluid got truly close to the critical point. Second, near-critical fluids compress under their own weight in Earth's gravity, so the density (and the bulk viscosity) becomes a function of the vertical position. Thus gravity places a limit on the smallest reduced temperature for which true critical behavior is observed.

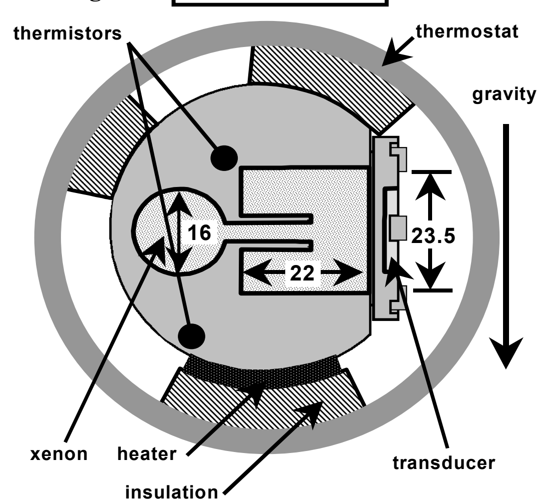


Figure 1: ***The schematic is a cross section of the acoustic resonator and the inner shell of the thermostat. All dimensions are in mm. The duct's diameter was 4 mm and its length was 15 mm. The xenon-filled volume was 20 cm³.***

The present experiment (BVX) uses a low-frequency (100 Hz to 6 kHz) acoustic resonator to deduce $\zeta(t,\omega)$ from measurements of the acoustic attenuation and the dispersion of the velocity of sound.

These frequencies are 4000 times lower than the frequencies used in previous bulk viscosity measurements. The low frequencies permit measurements of the bulk viscosity with $\omega\tau < 1$, down to $t = 2\times10^{-5}$, which is 100 times closer to T_c than previous measurements. Furthermore, the present experiment uses convective stirring to suppress the density gradients in Earth's gravity. (NASA had planned to operate the BVX experiment on the International Space Station; however, this plan was abandoned after the Columbia Shuttle tragedy.)

We developed the technique of heating the near-critical xenon from below, thereby, forcing convection and stirring. Without stirring the effective height of the resonator was 12 mm; with stirring, the effective height was less than 0.5 mm. The graph below shows that without stirring, the resonance frequencies decreased with t and then leveled off at $t \approx 2\times10^{-4}$; with stirring, the frequencies leveled off when $\omega\tau = 1$, as predicted without gravity.

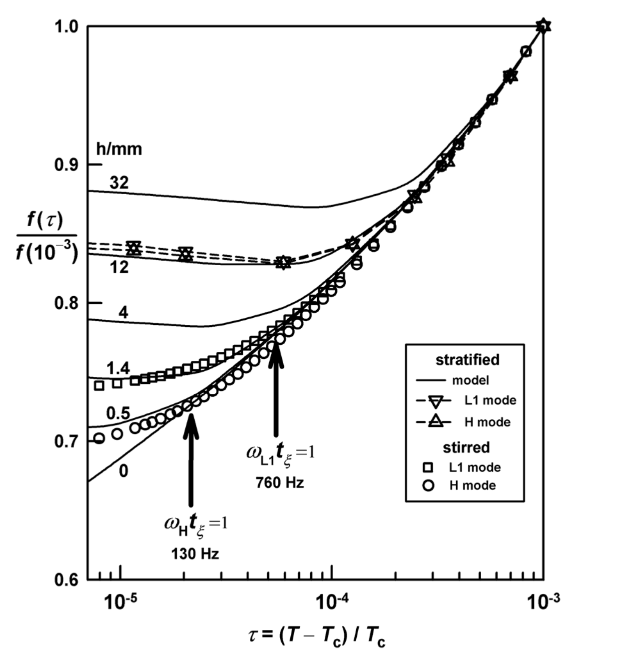
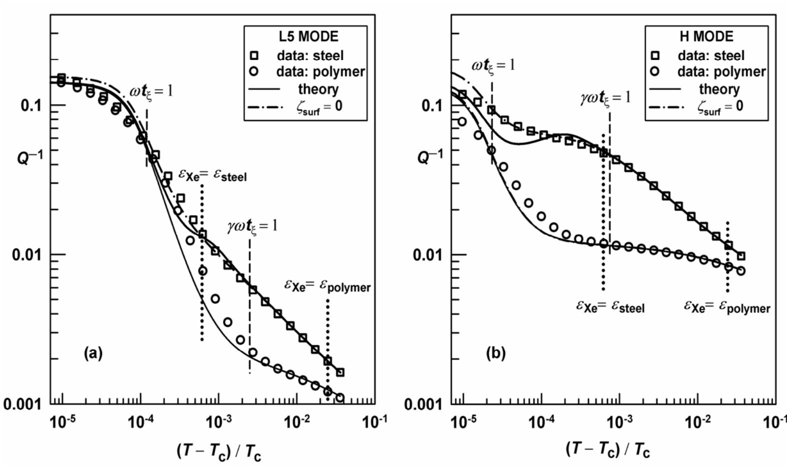


Figure 2: **Solid curves:** ***calculated frequency ratios for the horizontally propagating, longitudinal modes of a rectangular cell of various heights (h) in mm.***

Figure 2 continued: **Triangles:** ***frequency ratios in the polymer-coated resonator in equilibrium under gravity. Isolated points: frequency ratios in the polymer-coated resonator measured while the xenon was stirred by convection.***

As T_c was approached, the speed of sound $c(t,\omega)$ decreased by a factor of 2.2 (as seen in the previous graph) and the dissipation Q^{1} increased by up to a factor of 140, as seen in the graphs below.

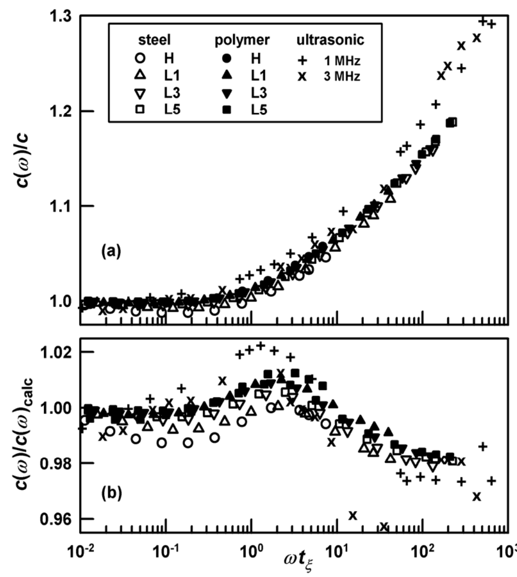


The dissipation Q^{-1} as a function of reduced temperature for (a) the fifth longitudinal mode, L5, and (b) the Helmholtz mode, H. In both graphs, the symbols denote measurements in the steel and polymer-coated resonators. The solid curves are calculated from the model.

Future Plans: The NIST Team plans to extend the measurement of the speed-of-sound and the bulk viscosity in xenon to non-critical densities using an improved resonator.

Publications: Gillis, K.A., Shinder, I.I., and Moldover, M.R., **"Bulk Viscosity of Stirred Xenon Near the Critical Point,"** Phys. Rev. E **72**, 051201 (2005).

Remarkably, these results are predicted (within ±2% of c and within a factor of 1.4 of Q) by our model for the resonator [Gillis, Shinder, and Moldover, Phys. Rev. E **70**, 021201 (2004)] and by a model for the frequency-dependent bulk viscosity $\zeta(t,\omega)$ that uses no empirically determined parameters. Furthermore, this model is consistent with ultrasonic (0.4 MHz to 7 MHz) velocity and attenuation data from the literature. [J. Thoen and C.W. Garland, Phys. Rev. A **10**, 1311 (1974).]



The top graph shows the measured dispersion for the speed of sound in xenon as a function of $\omega\tau$. The open and solid symbols are data from the steel (polymer-coated) resonator. X and + denote ultrasonic data from the literature. The bottom graph illustrates the ratio of the experimental to calculated speeds of sound as a function of $\omega\tau$.. The calculated dispersion $c(\omega)_{calc}$ is based on an approximate expression for the bulk viscosity with no adjusted parameters.